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IN-SITU MHD ENERGY CONVERSION FOR FUSION

R. B. Campbell
B. G. Logan
M. A. Hoffman

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Lawrence
Livermore
National
Laboratory

IN-SITU MHD ENERGY CONVERSION FOR FUSION*

R. B. Campbell
TRW Corporation
Redondo Beach, CA 90278
(415) 423-0707

B. G. Logan
Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550
(415) 422-9816

M. A. Hoffman
University of California--Davis
Davis, CA 95616
(916) 752-2630

ABSTRACT

An advanced concept, in-situ MHD conversion, is described for converting fusion energy to electricity. Considerable cost savings can be realized because of the conversion of thermal energy to electricity achieved in the blanket by means of magnetohydrodynamic (MHD) generators. The external disk generator, also described, is another application of the MHD idea, which may have certain advantages over the in-situ scheme for advanced-fuel tokamaks. The feature that makes these schemes fusion-specific is the novel use of the electromagnetic radiation naturally emitted by the plasma. The synchrotron radiation can be used either to heat the nonequilibrium MHD plasma, or possibly improve its stability. A Rankine cycle with cesium-seeded mercury as a working fluid is used in either case. Performance predictions by a quasi-one-dimensional model are presented. An experiment to determine the effect of microwave radiation on channel performance is planned.

1. INTRODUCTION

In this paper, an advanced concept, in-situ MHD conversion, is described for converting the energy released by fusion into electricity without relying on the conventional balance of plant (BOP). The conversion is achieved in the blanket (i.e., "in-situ") by means of magnetohydrodynamic (MHD) generators. Considerable cost savings can be realized by eliminating the standard external power conversion equipment, associated piping, and building and land costs. Most fusion reactor design studies[1,2] arrive at a direct capital cost approximately twice the cost of a conventional fission plant of the same power output. The fusion reactor is as expensive as the BOP; for fission, the reactor core costs about a tenth of the BOP. Fusion proponents argue that the low cost of fuel and environmental advantages of fusion will make it a legitimate competitor in the timeframe of its introduction as an energy source. While these arguments are certainly important ones, if the capital cost could somehow be reduced to the levels of fission, an even stronger argument for fusion could be made. The fusion reactor itself is a complex, expensive piece of equipment; reducing its cost by large factors may prove difficult with our present of knowledge. Here, we seek large factors of cost reduction by taking the approach of reducing the cost of the power conversion system.

The feature that makes the scheme fusion-specific is the use of the synchrotron radiation naturally emitted by a hot, magnetically confined plasma. For a deuterium-tritium (D-T) fuel cycle, the magnetic fields and plasma parameters can be chosen so that the synchrotron power is about 10% of the fusion power at moderate power density. For advanced fuels, in particular the deuterium-helium-3 (D-He3) cycle (fueled by He3 obtained from lunar sources),[3] this power can be a much larger fraction of the fusion power, up to 40%. This radiation can either be used to superheat the working fluid at the entrance of the generator, or can be applied along the length of the generator to enhance the performance of the MHD energy conversion process. Thermodynamic arguments, as well as the results of our model calculations, indicate that if the only benefit of using the radiation is to heat the MHD working gas, then it is better to use it to superheat. If instead, the radiation does something to the properties of the plasma in

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the channel, for example improves its stability, then it may be better to partition it for both superheating and heating along the channel. Based on our current understanding, our channels do not fall in the proper regime to take credit for stabilization, but experiments may prove otherwise.

We have devised several ways to use this in-situ concept in both tokamak and mirror geometries, for both D-T and D-He3 fuel cycles. The original idea used Faraday generators in the mirror geometry, shown in Fig. 1. More recently, the idea has been adapted to the tokamak geometry, shown in Fig. 2, with limited success, due to the large number of MHD generators required. For comparison to the in-situ scheme for the tokamak geometry, we are also considering a single large disk-Hall generator, which is located below the reactor floor coaxially with the tokamak's major axis. For reasons discussed in Section 5, this scheme may have important advantages over the strict in-situ embodiment of the concept in the case of advanced fuel cycles, such as D-He3.

A computer code has been developed, as described in Section 3, to calculate parameters of the various MHD generators considered in the study. The quasi-one-dimensional fluid equations with MHD body forces and plasma-related equations are solved as a function of the coordinate along the channel. Coupled to this is a thermodynamic calculation to determine Rankine cycle efficiencies, enthalpy extractions, and generator efficiencies. Examples of the results of these calculations for Faraday-type generators are shown in Tables 1 and 2, and are discussed in Section 4.

An experiment is being designed to test the idea of using synchrotron radiation to enhance the performance of an MHD generator. The experiment would examine the effects of applying the radiation as superheat, as well as applying it along the channel. The frequency of radiation would be based on predictions of our present theories so that a stabilizing effect would be observed.

Section 6 is devoted to conclusions, and areas for further work. Although this concept is currently in an embryonic state, its potential benefit in making fusion economically competitive warrants a much closer look at its engineering and economic feasibility.

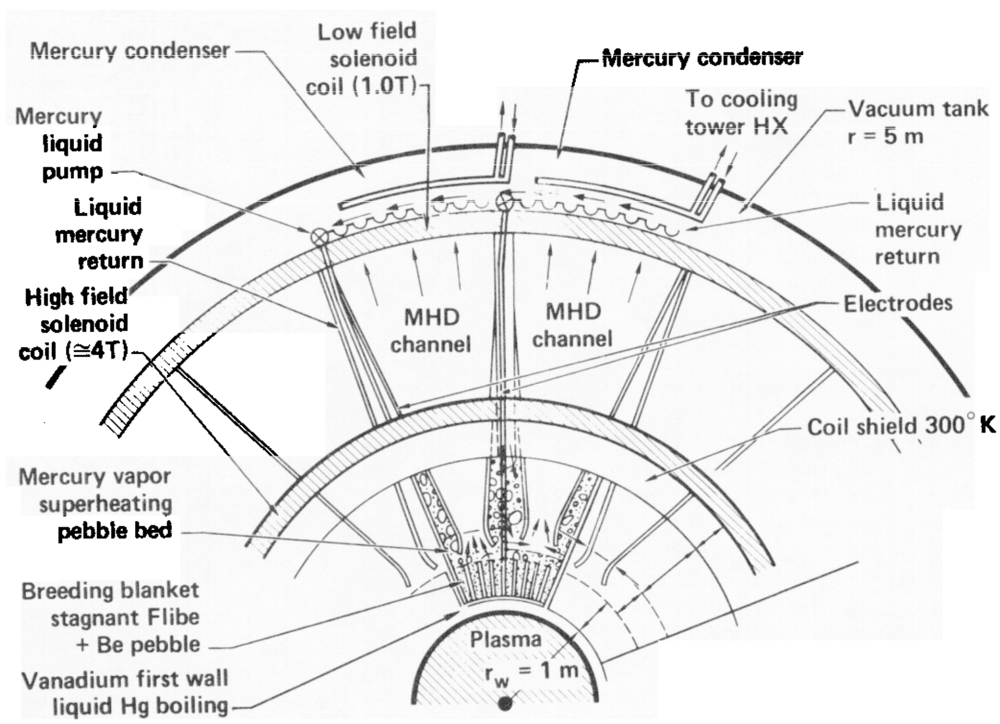

Figure 1. Basic in-situ MHD concept for mirror gemoetry.

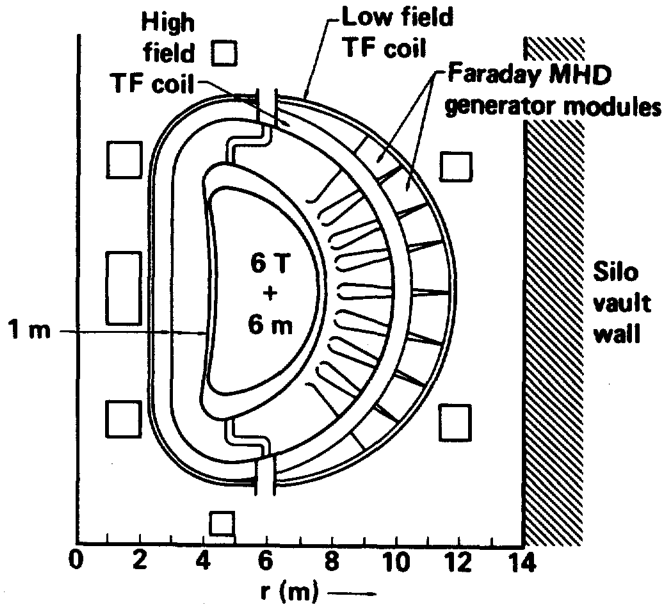

Figure 2. In-situ concept applied to tokamak geometry.

2. THE BASIC IN-SITU SCHEME

Figure 1 shows the in-situ MHD blanket concept using the Rankine thermodynamic cycle. Thermal energy from the fusion reaction is used to boil and, in D-T reactor cases, superheat a working fluid in the blanket. The superheating would be done in an intermediate pebble bed region where the thermal energy heating the pebbles would be from the neutrons. In a D-T reactor ~20-25% of the total blanket neutron and gamma heat can be generated in a high-temperature pebble-bed zone behind a tritium-breeding blanket zone. For example, this is sufficient to superheat mercury vapor to ~1750°K.

The electromagnetic radiation from the plasma, in the form of synchrotron and bremsstrahlung, can be used in several ways. The bremsstrahlung, because it is readily absorbed in walls, will be part of the thermal energy from the fusion process, which will contribute to the boiling of the working fluid. The synchrotron radiation can be used to superheat the gas at the inlet of the channel, or can be routed to various locations along the MHD duct.

The way in which the synchrotron radiation couples with the MHD duct plasma is through the mechanism of electron oscillation in the electric field of the wave. The electrons then transfer their energy to the gas atoms by means of electron-neutral collisions. This feature makes the heating quite unique because we may have more control over the spatial deposition profile of the synchrotron input power than we have in conventional methods of heating gas. Since this portion of the thermal energy does not pass through a material wall by conduction, as with other superheating schemes, the prospects for

Table 1. Impact of X on system performance: local deposition.

Case No.	X	R	P_{in} (atm)	H_{in} (m)	T_{out} (°K)	Cycle efficiency (%)	
1	0.0	51	0.72	0.34	665	27.2	(20.9)
2	0.2	90	1.33	0.25	765	30.3	(22.8)
3	0.4	115	1.83	0.21	916	32.0	(24.0)

Table 2. Impact of X on system performance: Superheat.

Case No.	X	T_{in} (°K)	R	P_{in} (atm)	H_{out} (m)	T_{out} (°K)	Cycle efficiency (%)	
4	0.2	2000	58	0.71	1.7	674	31.4	(25.6)
5	0.5	2750	80	0.75	2.0	736	41.0	(35.6)
6	0.7	3750	130	0.90	5.3	783	50.0	(43.0)

keeping the material temperatures reasonable while achieving high gas temperatures is much improved.

The generator is located in the back region of the blanket, which is made of materials that can withstand the temperatures required for efficient MHD power conversion (at least 1750°K for generators that operate with nonequilibrium ionization). The baseline concept uses a linear generator wired in the Faraday configuration, where two opposite walls comprise the electrodes, and the power extracting voltage drop occurs between these electrode walls, perpendicular to the gas flow direction. The enthalpy contained in the gas is extracted in the manner usual to MHD, and the working gas (typically mercury vapor seeded with a small amount of cesium) is condensed after the generator exit. A liquid-metal MHD pump is used to return the working fluid to the front of the blanket. The MHD pressure drop and stress problems associated with pumping the liquid metal across magnetic field lines must be addressed.

It is important to understand why we chose the Rankine cycle over the Brayton cycle. A complete Rankine cycle can be contained in a relatively small volume. A Rankine cycle results in a simpler design with reduced piping (undoubtedly nuclear-grade) and structures. This translates to increased availability and reduced costs. Another point is that because the Rankine cycle requires no lossy and expensive recuperators and compressors, the real cycle efficiencies can be made closer to ideal. For Rankine cycles, most of the heat transfer is in the boiling process, which results in lower mass flow rates through the blanket because the enthalpy of vaporization is typically large for candidate working fluids. However, liquid metals may pose a serious MHD pumping problem, as mentioned above, and some solution such as the use of mist flow[4] may be required.

There are three basic requirements for high-efficiency Rankine cycles. First, the cycles need large stagnation pressure ratios between inlet and outlet (from 30 to >100) to achieve good efficiency. The physical size of the condenser places a lower limit on the exit pressure for a given magnet and blanket geometry. Second, the cycle needs high temperature to work efficiently. Third, the cycle must use superheated vapor, to keep the local temperature above the dew point. This latter concern is especially true for MHD channels since droplets should not be allowed to form anywhere in the duct, to avoid quenching the nonequilibrium ionization.

Isotopically tailored mercury that is seeded with cesium was chosen as the working fluid for these initial calculations. Isotopes are eliminated that inhibit tritium breeding and that create long-lived radionuclides. We chose mercury because it was the liquid metal with the lowest boiling point at pressures of interest. For many materials, the superheated dry vapor does not pose a material-compati- bility problem as long as free oxygen is eliminated from the system. Mercury has a large ionization potential (10.8 eV) and has an electron-energy-level structure that makes line radiation small until the electron temperature gets above about 5000°K.

3. COMPUTER MODEL

For the purposes of evaluating possible channel and cycle options, we have been developing a steady-state, quasi-one-dimensional code to model the performance of an MHD generator coupled to a Rankine cycle. We have tried to keep the code general. It can model seeded plasmas with both equilibrium and nonequilibrium ionization, with the choice of working fluid and seed atom arbitrary. The generator geometry is also flexible; linear generators wired in either the Faraday or Hall configuration can be modeled, as well as the disk-Hall geometry.

The code solves the one-dimensional forms for the equations of continuity (both mass and current), energy, and momentum along the duct. At each point along the generator, several auxiliary equations are solved. The Saha equilibrium equations are solved for both the singly-ionized seed and parent gas atoms. Also solved is an electron-energy balance that contains heat sources resulting from synchrotron radiation and joule heating, and sinks resulting from electron-neutral and electron-ion collisions, as well as line radiation. Finally, a calculation of the effective electrical conductivity of the channel plasma is performed. This takes into account the finite pitch of electrode/ insulator pairs in the Faraday case, as well as the reduction in conductivity due to nonuniformities caused by electrothermal instabilities. A stability formalism summarized by Solbes[5] is used, with modification for the case when the spectral shape of the synchrotron radiation is favorable for stability,[6] as well as the case when the parent gas becomes appreciably ionized.[7]

In the basic differential equations we solve, we try to put in some realism by including quasi-one-dimensional models of the friction and heat transfer losses. These models are adequate for a scoping study of large generators, but for small experimental ducts they tend to be too pessimistic. We presently include the electrode voltage drop across the duct boundary layer parametrically since we have as yet no models in the code to compute the boundary layer profiles which are important in determining this voltage drop. Our philosophy has been to keep the modeling simple initially, yet try to include the major effects.

4. FARADAY-GENERATOR CALCULATIONS

The computer code described above has been applied to answer the question of how the cycle efficiency improves when synchrotron radiation is added to the MHD generator cycle in two different ways. In the first set of calculations, the inlet stagnation temperature was held constant at 1750°K, and the ratio of the local synchrotron power density to electrical-power density generated X was varied. A second set of cases also varied X, but used the power to superheat above the nominal 1750°K at the inlet. The efficiencies in parentheses are those calculated assuming a large (100 V) drop in the electrode boundary layer; the other efficiencies are for no electrode voltage drops. The benefit of the synchrotron radiation is assumed to be only as an additional source of thermal energy to heat the electrons. The constraints imposed are a fixed generator length (2.5 m), mass flow rate (15kg/s), inlet Mach number (2.0), and outlet Mach number (~1). An additional constraint is that the enthalpy flow at the generator inlet divided by the generator exit area is held fixed at 1.1 MW/m^2, which is approximately equivalent to fixing the first-wall loading. A final constraint imposed is that the local static gas temperature remain above the saturation temperature at all points along the duct. To satisfy these constraints, the inlet stagnation pressure, stagnation pressure ratio, inlet channel height (channels are of square cross section), and cesium seed fraction are varied. Tables 1 and 2 show the results of these calculations.

These results are plotted on Fig. 3, which shows the relationship between efficiency and synchrotron fraction for the two methods of using the synchrotron radiation, for the case ignoring the electrode boundary layer voltage drops.

Figure 4 shows typical plots of various MHD channel parameters as a function of channel length.

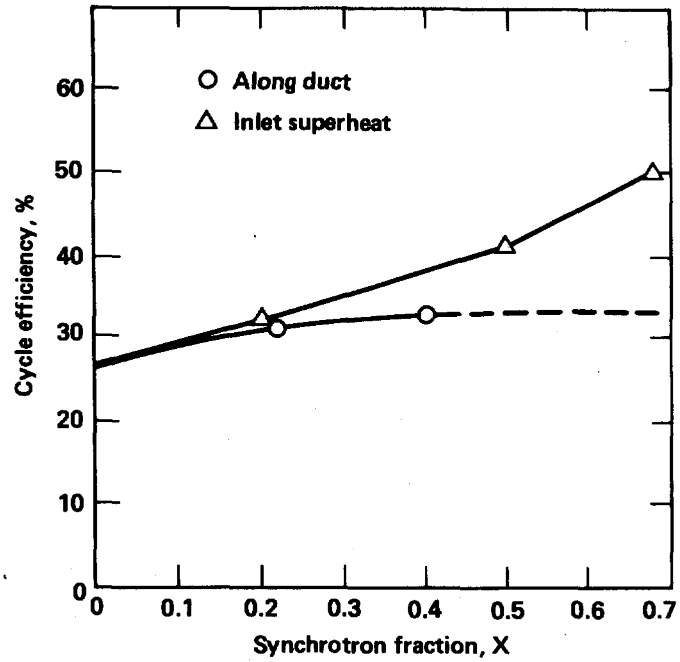

Figure 3. Cycle efficiency as a function of synchrotron fraction.

First note from both Fig. 3 and Tables 1 and 2 that the superheating method is preferable to the local deposition scheme, given the assumption in the calculation that the synchrotron radiation acts only as a heat source. For case 6 with X = 0.7, which is not out of the question for an advanced fuel application, the cycle efficiency lies between 43 and 50%. Recall that the unique feature of synchrotron superheating a gas is that it allows us to selectively heat the core flow; hence, the material walls can be much cooler than 3750°K. In both tables, note that an important benefit of the radiation is to allow expansion to a larger stagnation pressure ratio R and still remain above the dew point. Table 1 shows that the inlet channel height must get smaller and the inlet pressure larger as the synchrotron fraction increases. The constraint of constant generator-exit heat load fixes the outlet height, so the channels are more flared at the higher synchrotron fractions. Greater flaring at higher X is also true for the superheated cases.

Note the strong effect of the electrode boundary-layer voltage drop in computing the power extracted in these relatively small generators; the cycle efficiency can be lowered by as much as six or seven percentage points.

High cycle efficiency requires substantial increases in the channel flow area. This is a

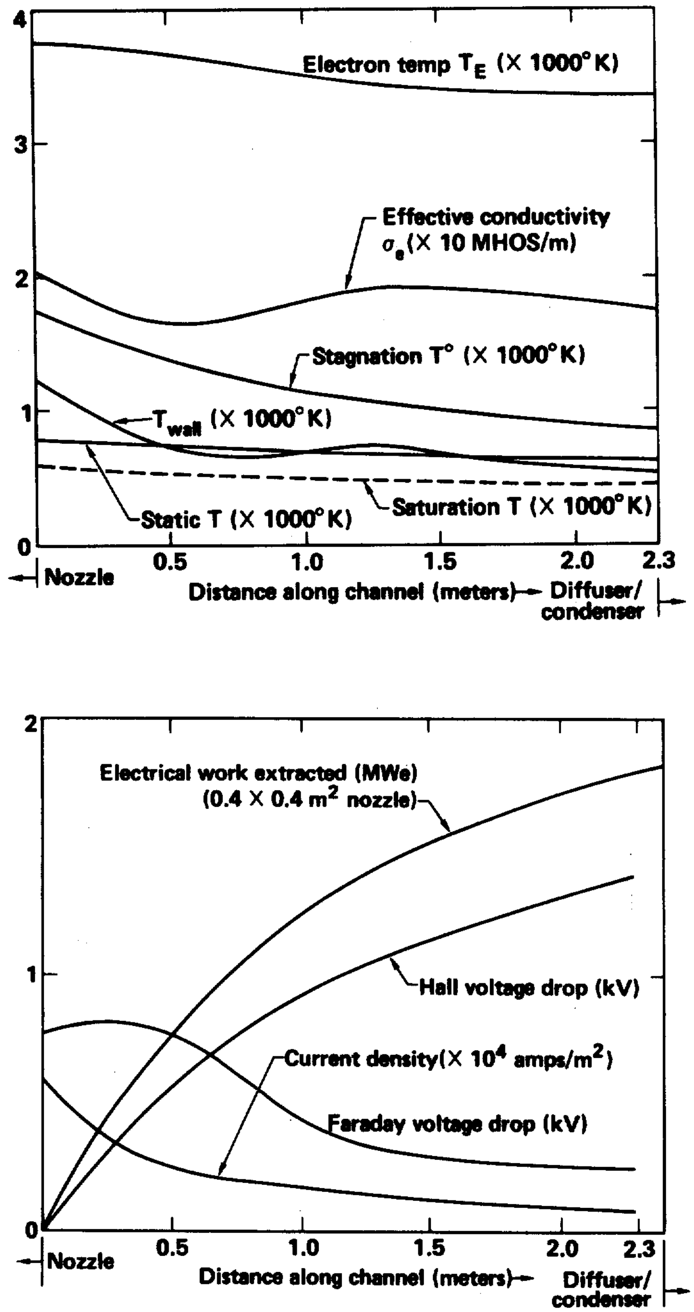

Figure 4. Channel parameter profiles for case 2.

characteristic shared by other efficient high-pressure-ratio enthalpy-extracting devices, such as turbines. Figure 5 compares the MHD channel cross sections for the cases in Tables 1 and 2.

The cases 1-3 show that when we heat along the duct and observe the described constraints, the gas temperature change from inlet to outlet is smaller than if no radiation were used. The enthalpy extraction then, from the classic definition relating it to a temperature difference, actually is less when synchrotron is present. Where we gain the modest improvement in efficiency is in our ability: (1) to expand to a higher pressure ratio while still staying above the dew point, (2) to use a higher local load factor along the channel, (3) to increase heat available for preheating the liquid (regeneration), and (4) to convert with MHD the radiation heat input. On the other hand, the introduction of the radiation cases 4-6, to give the high superheat temperatures, allows the inlet to outlet ΔT to become much larger, up to 3000°K for case 6. This explains the dramatic improvement in efficiency when synchrotron is used to heat the gas at the generator inlet.

5. AN EXTERNAL DISK-HALL GENERATOR

Figure 6 is a simplified sketch of another way to use MHD generators in a fusion

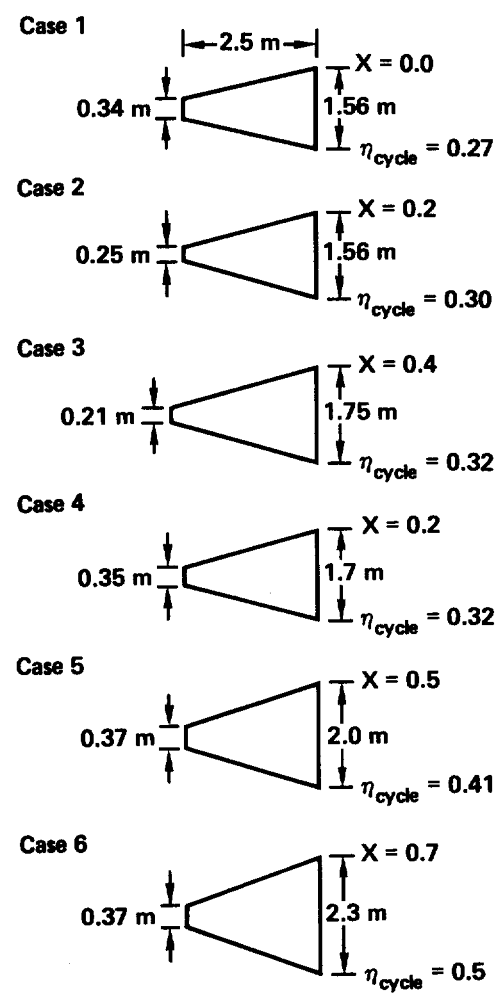

Figure 5. Channel cross-section profiles for cases 1-6.

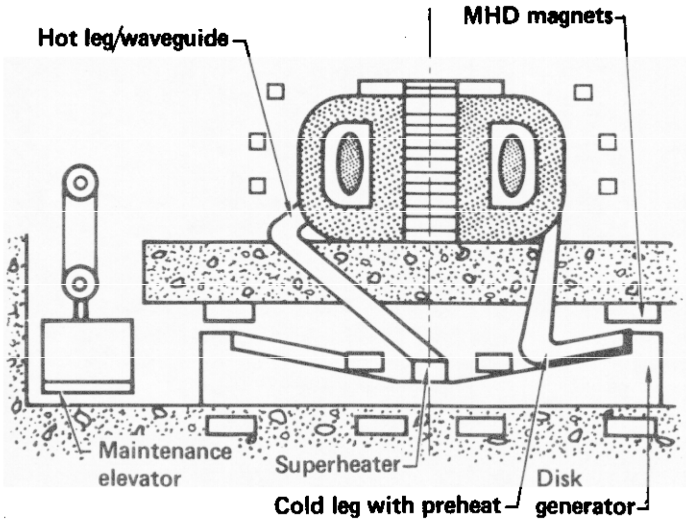

Figure 6. External disk generator.

application. The idea could have advantages for implementation in a tokamak geometry, where the space for generators is particularly limited. Most of the superheating can be done with synchrotron radiation if we want to keep the blanket temperature low since the superheat region now occurs outside the blanket. This probably limits the use of this scheme to reactors using advanced fuels because much more synchrotron will be available in these devices.

Note that the hot-leg pipe of the mercury loop can also serve the function of the waveguide to transport the synchrotron (microwave) radiation. The electrical conductivity of mercury vapor is quite low at the gas temperatures in the pipe, and the operating pressures and microwave frequencies are high enough that breakdown in the waveguide is not expected to be a problem. Consequently, absorption of the microwaves occurs only in the seeded gas, and seeding will occur in the superheating chamber indicated in Fig. 6. Loss of synchrotron power in the waveguide due to skin effects in the wall has been examined and found to be small (5% for a run of 45 m) for a square channel with dimensions of 1 m or so.

Because of the very high temperatures in the superheating chamber, it would most probably be made of some kind of ceramic material. The cold leg of the loop would incorporate preheat of the liquid mercury from the heat loss on the walls of the generator. Maintenance of the generator would be accomplished by means of specially-designed machines which would gain access by means of an elevator.

The external disk has several advantages when compared to the in-situ Faraday generators. The disk-Hall generator might be better because it has no electrode walls. One of the assumptions implicit in using the Faraday generators in the in-situ scheme is that the electrode-wall problem can be solved by careful choice of materials and operating modes. A major concern in regard to the Faraday generators is the shorting of the Faraday current in the electrode boundary layer. The results of twenty-five years of research in linear generators indicate that this is a difficult problem,[8] particularly for the nonequilibrium supersonic generators we propose here. The data obtained by the Japanese using the Disk-II generator[9] employing nonequilibrium ionization in the supersonic regime supports the ability of the disk to perform under our conditions.

Work by Hoffman[10] shows that as the power output of a nonequilibrium Faraday generator increases, the generator efficiency improves dramatically. We show the same to be true for nonequilibrium disk generators. The improvement is related to the diminished importance of nonideal effects; voltage drops, radiation, heat transfer, and friction. Small in-situ disks are dominated by nonideal effects and have poor performance. It is therefore advantageous to build generators each of which will convert a large fraction of the thermal power input. In the in-situ scheme, each generator will convert only a small fraction of the thermal power due to size limitations, thereby not taking advantage of the favorable size scaling. In the external disk, all the power can be converted by one or two generators, if desired.

Another important advantage of the external disk generator is the reduced blanket temperatures. Superheating in the chamber directly in front of the entrance to the generator will provide more than 2000°K of temperature rise. This means that the blanket temperatures can stay in the range of 700-900°C, where materials issues have been more extensively studied.

A related advantage of the external disk generator is that without the MHD channel and superheat regions in the blanket, more of the blanket volume can be used for heat transfer. This should make the design of the blanket more like "conventional" fusion blankets, not having to rely on all the heat being absorbed in the first 30 cm.

It is possible that these advantages of the external disk could outweigh the requirement of a modest increase in piping and the purchase of a few simple circular magnets. Cost and feasibility studies of both the in-situ and the external schemes must be performed to decide which one is more attractive.

Table 3 shows the characteristics of a single disk generator designed to convert about 3000 MW of thermal power, consisting of neutrons, plasma convective power, and bremsstrahlung. The fusion driver for this case is a 5000 MW fusion power D-He3 fueled tokamak, producing about 2000 MW of synchrotron radiation.

Table 3. Characteristics of external disk generator.

Parameter (unit)	Value
Inner radius (m)	2.50
Outer radius (m)	10.65
Inlet height (m)	0.70
Outlet height (m)	6.50
Inlet magnetic field (T)	10.0
Outlet magnetic field (T)	0.75
Inlet stagnation temperature (°K)	3250.0
Wall temperature (°K)	800.0
Outlet stagnation temperature (°K)	1525.0
Inlet stagnation pressure (atm)	20.0
Stagnation pressure ratio	400.0
Cesium seed fraction ($\times 10^{-4}$)	1.42
Inlet Mach No.	2.0
Outlet Mach No.	1.20
Electrode voltage drop (V)	100.0
Inlet velocity swirl ratio, U_i/U_r	1.50
Electron temperature(°K)	3500.0
Mass flow rate (kg/s)	6000.0
Hall current (kA)	291.0
Enthalpy extraction (%)	51.0
Generator efficiency (%)	56.0
Total heat input to cycle (MW)	2900.0
Electrical power extracted (MW)	1029.0
Cycle efficiency (%)	35.50

Note the large stagnation pressure ratio possible with this configuration. We operated the code in a mode where the the electron temperature was held constant at 3500°K, and the magnetic field was tailored to satisfy the electron-energy balance. This facilitated obtaining solutions with the required performance. In the Faraday channel calculations we described earlier, the axial profile of the magnetic field was fixed, and the external loading was adjusted instead. Because there is only one set of electrodes in a disk generator, which means we have to satisfy axial current continuity, this freedom of choosing the loading was not available to us. The computed field profile dropped off very rapidly with radius, as did the electrical power density. However, significant power was extracted, because of the volume increase as the duct flares out.

The cycle efficiency thus far obtained is modest, although the enthalpy extractions and generator efficiencies are rather good, by MHD standards. For comparison, standard light-water reactor (LWR) cycle efficiencies are similar, and a more advanced cycle like that in MARS[2] is about 43%. What must be remembered is that a modest cycle efficiency can be tolerated if the capital cost is greatly reduced, which is the goal of the MHD scheme. The efficiency of the generator could be improved if the channel were divided into stages, with an intermediate electrode to extract some of the power. This would alleviate the axial current continuity constraint somewhat, and allow the channel to be run at a higher average loading and magnetic field, thereby extracting more electrical power.

6. CONCLUSIONS AND FURTHER WORK

The in-situ scheme for MHD energy conversion applied to fusion is a potentially attractive way to eliminate a large capital cost item, the balance of plant. Our present assessment of the concept indicates that it appears workable. The definition of an experiment, using microwaves for superheating and for possible stabilization of electrothermal instabilities in the non-equilibrium MHD generator, is a priority. Channel modeling must continue, particularly in the area of a more accurate treatment of the boundary layer, which is critical in predicting the performance of the experimental-size ducts. We must also begin modeling the microwave-gas interaction, and its associated efficiency. Finally, a more detailed conceptual design study should be undertaken to define and investigate critical issues pertaining to the engineering and economic feasibility of the scheme.

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